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(54) Title: LONG PULSE VANADATE LASER

(57) Abstract

A diode-pumped solid-state laser has been invented that provides long Q-switched pulses at high repetition rate with high stability. The laser incorporates Nd:YVO_4 as the gain medium.

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LONG PULSE VANADATE LASER

FIELD OF THE INVENTION

This invention relates to diode-pumped solid-state lasers, and in particular to diode-pumped solid-state lasers that provide long pulses at high repetition rate with high stability.

BACKGROUND OF THE INVENTION

Diode-pumped Nd:YVO_4 lasers have been used in applications that require short pulses (< 20 nsec) at high repetition rates (> 10 kHz). See for example M.S. Keirstead, T.M. Baer, S.B. Hutchison, J. Hobbs, "High repetition rate, diode-bar-pumped, Q-switched Nd:YVO_4 laser", in Conference on Lasers and Electro-Optics, 1993, Vol. 11, OSA Technical Digest Series (Optical Society of America, Washington, D.C., 1993), p. 642, and S.B. Hutchison, T.M. Baer, K. Cox, P. Gooding, D. Head, J. Hobbs, M. Keirstead, and G. Kintz, *Diode Pumping of Average-Power Solid State Lasers*, Proc. SPIE 1865, 61 (1993). These reports describe operation of Nd:YVO_4 lasers in a manner that provides short pulses at high repetition rate, as does W.L. Nighan, Jr., Mark S. Keirstead, Alan B. Petersen, and Jan-Willem Pieterse, "Harmonic generation at high repetition rate with Q-switched Nd:YVO_4 lasers", in SPIE 2380-24, 1995, which discloses generation of Q-switched pulses with an end-pumped, acousto-optically Q-switched laser.

In Nighan et al, pulse durations of 7 - 20 nsec were generated for repetition rates of 10 - 80 kHz, at an average output power of ~ 4 W in a TEM_{00} mode. The pump source was a fiber-coupled diode bar, as disclosed in US Patents 5,127,068 and 5,436,990. End-pumping of Nd:YVO_4 with a pump source like this fiber-coupled bar allows generation of very high small signal gain, since this material has a stimulated emission cross-section that is much higher than that of Nd:YLF or Nd:YAG. This is useful for building a diode-pumped laser with a low laser oscillation threshold, and is also useful for building a laser that provides short pulses at high repetition rates. However, the short upper state lifetime of this material (~ 100 μsec) does not allow as much energy storage as is possible with Nd:YLF (500

μsec) or Nd:YAG (200 μsec), which limits the amount of pulse energy that can be generated at repetition rates below 10 kHz. For example, an $Nd:YVO_4$ laser pumped at 10 W can provide 200 μJ at low repetition rates, while the YLF laser (designated "TFR" by Spectra-Physics Lasers, described by T.M. Baer, D.F. Head, P. Gooding, G.J. Kintz, S.B. Hutchison, in "Performance of Diode-Pumped Nd:YAG and Nd:YLF in a Tightly Folded Resonator Configuration", IEEE J. Quantum Electron., vol. QE-28, pp. 1131-1138, 1992) provide ~ 800 μJ.

While short (<20 nsec), energetic pulses are typically desired for many applications, especially at high repetition rate (>10 kHz), there are some applications that require long Q-switched pulses, such as pulses on the order of 50 nsec. In the prior art, the material Nd:YVO4 has not been applied to long pulse operation at high repetition rate, since it is typically well-suited for short-pulse generation. It is well-known that a CW-pumped, repetitively Q-switched laser will provide progressively longer pulses if the repetition-rate of the laser is progressively increased. This is described in "Lasers", by Siegman, in Chapter 26. The reason for this effect is simple. As repetition rate is increased (at rates higher than the reciprocal of the upper state lifetime), the maximum amount of energy stored in the gain medium between Q-switched pulses decreases; this stored energy is proportional to the density of ions in the upper state just before Q-switching. This means that the small-signal gain is decreased, since the small-signal gain depends upon the density of ions still in the upper state. If the small-signal gain is reduced, as it is by increasing the repetition rate, the Q-switched laser pulse will not build up as rapidly in the laser cavity as it would at lower repetition rate. Therefore, the pulse will be longer.

A number of diode-pumped Nd:YLF lasers, available from Spectra-Physics as the R-series, provides pulses of < 10 nsec duration (short) at 1 kHz (low repetition rate). If the repetition rate is increased to over 10 kHz (high repetition rate), the pulse durations on the order of 50 nsec (long) can be achieved. Although short pulses are typically desirable, long pulses (> 20 nsec, for example) can be useful for certain applications, especially at high repetition rate. However, the pulse-to-pulse stability of an Nd:YLF laser at high repetion rate can be poor; for

example, the peak-to-peak fluctuations of an Nd:YLF laser at repetition rates over 10 kHz can easily be 50%, which can correspond to an RMS noise of ~ 8%, which is too noisy for some applications. This increase in instability is common for a laser for which repetition rate has been increased; since less energy is stored, the laser oscillation is closer to threshold with each increase in repetition rate, and is therefore noisier. For applications that require greater stability at high repetition rate but still need longer pulses, there is a problem in straight forward applications of a low repetition rate laser operating at higher repetition rates; stability is decreased. Some applications require high stability, long pulses, and high repetition rate. An important range that has not been provided by the prior art is repetition rate greater than 25 kHz, pulse duration greater than 35 nsec, and RMS stability less than 5%.

In "A new laser texturing technique for high performance magnetic disk drives", by Baumgart et al (IEEE Transactions on Magnetics, Vol. 31, No. 6, Nov. 1995), it is disclosed that an Nd:YLF laser with 50 nsec pulses is used to provide a highly desirable texture to a magnetic disk, such as a disk used in a computer hard drive. The references and patents that were listed in the Baumgart paper are hereby incorporated by reference; they list a variety of laser-texturing prior art. The Baumgart paper shows that a slight change in pulse energy can change the shape of the "bump" that the single laser pulse leaves on the disk. Multiple bumps are typically left on the disk, as Baumgart describes. In some cases, there is a range of variation that is acceptable, as was disclosed by Baumgart. For this reason, there is a limit on the laser pulse-to-pulse variations that are acceptable. Also, as is obvious to one skilled in the art, a high repetition rate will allow a shorter time requirement for a laser texturing job to be completed.

There is a need for a long pulse, Q-switched laser that provides pulses at high repetition rate with high stability. There is also a need for a laser with harmonically converted output with high stability.

SUMMARY OF THE INVENTION

It is an object of the invention to provide a diode-pumped solid-state laser that provides long Q-switched pulses at high repetition rate with high stability.

It is an object of the invention to provide a diode-pumped solid-state laser that provides long Q-switched pulses at high repetition rate with high stability, with the solid-state laser incorporating Nd:YVO_4 as the gain medium.

It is an object of the invention to provide a diode-pumped solid-state laser that provides Q-switched pulses longer than 35 nsec, at repetition rates higher than 25 kHz, and with RMS noise of the pulsed output at less than 5%.

It is an object of the invention to provide a diode-pumped solid-state laser that provides Q-switched pulses longer than 35 nsec, at repetition rates higher than 25 kHz, and with RMS noise of the pulsed output at less than 5%, with the solid-state laser incorporating Nd:YVO_4 as the gain medium.

It is an object of the invention to provide a diode-pumped solid-state laser that provides long Q-switched pulses at high repetition rate with high stability, with the solid-state laser incorporating Nd:YVO_4 as the gain medium, with a harmonic generator included with the laser in order to harmonically convert the output of the laser.

It is an object of the invention to provide a diode-pumped solid-state laser that provides long Q-switched pulses at high repetition rate with high stability, with the solid-state laser incorporating Nd:YVO_4 as the gain medium, with this solid-state laser applied to a laser texturing application.

These and other objects of the invention are achieved in a diode-pumped solid-state laser, with an Nd:YVO_4 laser crystal placed in the resonator of the laser, said resonator incorporating at least two mirrors, with a Q-switch device placed in the laser resonator, with the pump power density and cavity lifetime balanced to provide long Q-switched pulses at high repetition rate with high stability.

In one embodiment, the laser resonator configuration is relatively symmetric, with the laser crystal placed nearly at the center of the laser resonator.

With this invention, Nd:YVO_4 has been incorporated for the first time in a

long pulse (>35 nsec), highly stable (< 5% RMS), high repetition rate (> 25 kHz) diode-pumped solid-state laser. In a preferred embodiment, it provides over 1 W in average output power.

DETAILED DESCRIPTION OF THE DRAWINGS

Fig. 1 is a diagram of a Q-switched, diode-pumped, Nd:YVO_4 solid-state laser that provides long pulses (>35 nsec), while highly stable (< 5% RMS), at high repetition rate (> 25 kHz). In some embodiments it provides over 1 W of average power.

Fig. 2 is a plot of the output pulse duration as a function of repetition rate, and the average output power as a function of repetition rate. The pump power was 5 W.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Fig. 1 depicts a diode-pumped Nd:YVO_4 laser that provides a long pulse (>35 nsec), that is highly stable (< 5% RMS) from pulse-to-pulse, even at high repetition rate (> 25 kHz). In a preferred embodiment, it provides over 1 W in average output power. In a preferred embodiment, it provides pulse of duration about 70 nsec at repetition rates of about 70 kHz.

As illustrated in Fig. 1 the laser includes an Output coupler 1 (typical reflectance is 95% at the 1.064 μm fundamental wavelength), with radius of curvature of 2 m to infinity, typically. All optics are available from Spectra-Physics Laser Components and Accessories Group in Oroville, CA..

The laser also includes a beam path 3, optimized in length with the output coupler 1 to provide adequate cavity lifetime to provide a long pulse. A preferred embodiment is 18 cm in length. Examples of other embodiments of the beam path 3 which may be used in the present invention are disclosed in U.S. Patent No. 5,412,683 and Application Serial No. 08/432,301, each of which are incorporated herein by reference.

The laser also includes a fold mirror 5 which is highly reflective at the 1.064 μm wavelength (R > 99.5%) and highly transmissive at the diode pump wavelength (T > 90%). This is a flat optic.

The laser also includes a $Nd:YVO_4$ laser crystal 7, available from Litton Airtron in Charlotte North Carolina, in dimension approximately 4 x 4 x 4 mm^3, and dopant about 0.7%. The laser crystal may be fixtured as described in U.S. Patent No. 5,412,683, and Application Serial Nos. 08/191,654 and 08/427,055, each of which are incorporated herein by reference.

The laser also includes an acousto-optic Q-switch 9, made of SF10 glass or any other glass, like fused silica, to provide adequate loss for Q-switching. A vendor of these devices is NEOS, in Melbourne Florida.

The laser also includes an end-mirror 11, highly reflective at 1.064 μm, radius of curvature from 2 m to infinity.

The laser also includes a Q-switch driver 13, providing RF of the appropriate frequency to the acousto-optic Q-switch, such as 80 MHz, at the appropriate power, such as 2 - 4 W, to provide controllable loss for Q-switching the cavity.

The laser also includes imaging optics 21, for relaying the light from a diode pump source into the laser crystal. These simple lenses are available from Melles Griot, Irvine, CA, and many other sources. A typical pump spot size is 0.5 to 0.6 mm, in the laser crystal.

The laser also includes fiber bundle 23, for relaying diode light to the imaging optics 21. One vendor for these bundles is Spectra-Physics Laser Components and Accessories Group in Oroville, CA.

The laser may also include an optional aperture stop 25, with appropriate size to insure TEM_{00} operation.

The laser also includes diode 15, for providing pump light to the solid-state laser. A common device is an OPC-B020-808-CS, available from OptoPower Corporation, Tucson, AZ. Six to eight watts from the diode is typical, with 5 to 6 exiting the bundle 23.

The laser also includes power supply 17, providing electrical power to the

diode and maintaining the diode temperature. Q-switch driver 13 is also typically housed in the power supply 17.

The laser also includes output beam 19, which is typically over 1 W in average power, with highly stable, long, Q-switched pulses.

The combination of diode-pumped $Nd:YVO_4$ in a cavity of appropriate length and cavity lifetime results in long pulses (> 35 nsec, with > 50 nsec in a preferred embodiment) at high repetition rate (> 25 kHz, with > 50 kHz preferred) at high stability (< 5% RMS). The high gain and short lifetime of $Nd:YVO_4$ combine with the cavity lifetime to provide this unique performance. This gain material has never been used in prior art to provide such long pulses at such high stability; this performance is required in some applications. The prior art with this material describes only short pulse generation (20 nsec), even at repetition rates as high as 80 kHz. An example of an application that requires longer pulses is magnetic disk texturing.

Fig. 2. depicts the performance of the laser of Figure 1. Pulses of duration approximately 70 nsec were obtained at approximately 70 kHz, in a highly stable beam. In a preferred embodiment, the laser output is TEM_{00}, which enhances focusability.

Changes and modifications in the specifically described embodiments can be carried out without departing from the scope of the invention which is intended to be limited only by the scope of the appended claims.

CLAIMS

What is claimed is:

1. A diode-pumped solid-state laser that provides long Q-switched pulses at high repetition rate with high stability, with the solid-state laser incorporating $Nd:YVO_4$ as the gain medium.

2. A diode-pumped solid-state laser that provides Q-switched pulses longer than 35 nsec, at repetition rates higher than 25 kHz, and with RMS noise of the pulsed output at less than 5%, with the solid-state laser incorporating $Nd:YVO_4$ as the gain medium.

3. A diode-pumped solid-state laser that provides Q-switched pulses longer than 35 nsec, at repetition rates higher than 25 kHz, and with RMS noise of the pulsed output at less than 5%, with the solid-state laser incorporating $Nd:YVO_4$ as the gain medium, with the laser used to provide a texture on the surface of a hard disk for a computer hard drive.

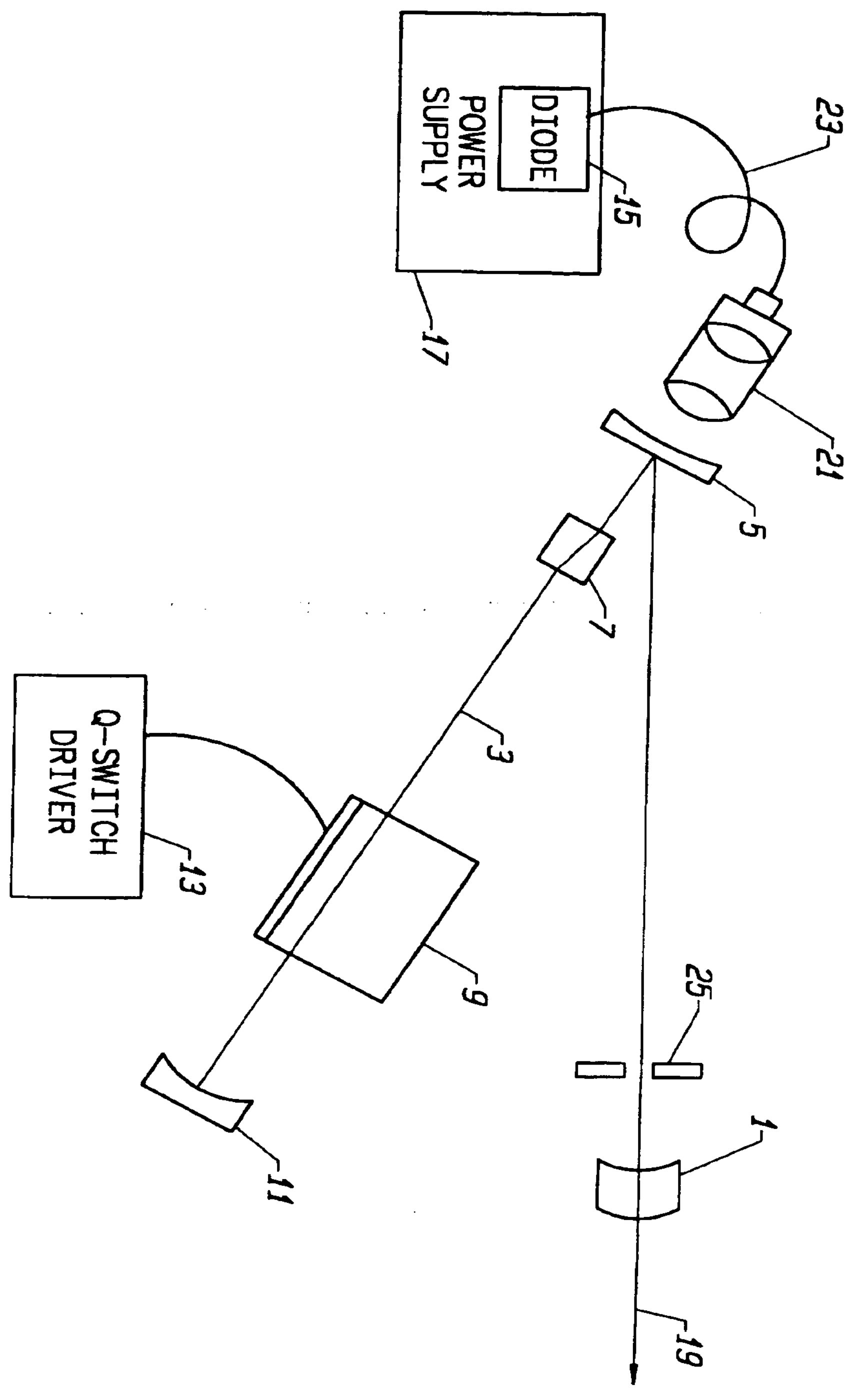
DIODE
POWER
SUPPLY
15
17
23
21
5
7
3
Q-SWITCH
DRIVER
13
9
25
1
11
19

FIG. 1

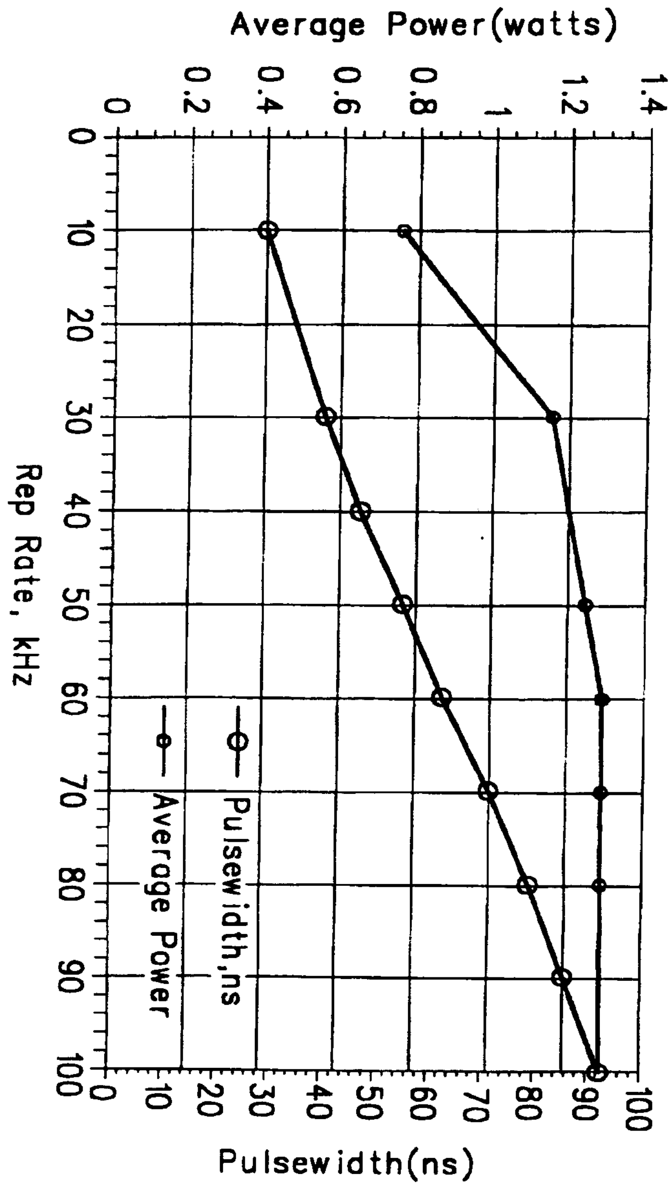
Average Power(watts)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Rep Rate, kHz
0
10
20
30
40
50
60
70
80
90
100
Pulsewidth,ns
Average Power
Pulsewidth(ns)
0
10
20
30
40
50
60
70
80
90
100

FIG. 2

INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/06887

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 H01S3/11 H01S3/0941 G11B5/84

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed byclassification symbols)
IPC 6 H01S G11B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	ZAYHOWSKI J J ET AL: "COUPLED-CAVITY ELECTRO-OPTICALLY Q-SWITCHED ND:YVO4 MICROCHIP LASERS" OPTICS LETTERS, vol. 20, no. 7, 1 April 1995, pages 716-718, XP000497429 see page 718, right-hand column, line 3 - line 25; figure 4 ---	1
Y	VLASENKO O A ET AL: "DIODE PUMPED ND3+:GDVO4 LASER WITH FIBRE INPUT" QUANTUM ELECTRONICS, vol. 25, no. 8, 1 August 1995, page 758/759 XP000535543 see figures 1,3 ---	2,3

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[X] Further documents are listed in the continuation of box C.

[ ] Patent family members are listed in annex.

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1

Date of the actual completion of the international search	Date of mailing of the international search report
13 August 1997	21/08/1997
Name and mailing address of the ISA	**Authorized officer**
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INTERNATIONAL SEARCH REPORT

International Application No
PCT/US 97/06887

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	ZAGUMENNYL A I ET AL: "THE ND:GDVO4 CRYSTAL: A NEW MATERIAL FOR DIODE-PUMPED LASERS" SOVIET JOURNAL OF QUANTUM ELECTRONICS, vol. 22, no. 12, 1 December 1992, pages 1071-1072, XP000359011 see the whole document ---	2,3
Y	BAUMGART P ET AL: "A NEW LASER TEXTURING TECHNIQUE FOR HIGH PERFORMANCE MAGNETIC DISK DRIVES" IEEE TRANSACTIONS ON MAGNETICS, vol. 31, no. 6, 1 November 1995, pages 2946-2951, XP000567629 cited in the application see abstract ---	3
A	NIGHAN W L ET AL: "HARMONIC GENERATION AT HIGH REPETITION RATE WITH Q-SWITCHED ND:YVO4 LASERS" PROCEEDINGS OF THE SPIE, vol. 2380, 7 February 1995, pages 138-143, XP000579455 cited in the application see abstract ---	1
A	PLAESSMANN H ET AL: "SUBNANOSECOND PULSE GENERATION FROM DIODE-PUMPED ACOUSTO-OPTICALLY Q-SWITCHED SOLID-STATE LASERS" APPLIED OPTICS, vol. 32, no. 33, 20 November 1993, pages 6616-6619, XP000413304 see figure 2 ---	1
A	HAMID HEMMATI ET AL: "HIGH REPETITION-RATE Q-SWITCHED AND INTRACAVITY DOUBLED DIODE-PUMPED ND:YAG LASER" IEEE JOURNAL OF QUANTUM ELECTRONICS, vol. 28, no. 4, 1 April 1992, pages 1018-1020, XP000272693 see page 1019, right-hand column, line 4 - line 8; figure 3 -----	1,2

1